MAGNET TECHNOLOGY

25-30 T Water Cooled Pulsed Magnet Concept For Neutron Scattering Experiment

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The Manuel Lujan Jr. Neutron Scattering Center, LANL, is in need of a split-pair, pulsed magnet that would provide a 25-30 T field in a 25 mm bore and 10 mm split gap for 2-4 ms at a repetition rate of 2 Hz. Single stack Bitter magnets of this type providing less than 20 T vertical field in the split gap have been constructed before. To produce higher fields, there is a need to use a multiple layer coil with internal reinforcement (Figure 1). The magnet should withstand up to 10^7 cycles of loading and unloading. Since superconducting magnets are limited to fields less than 20 T, a 25-30 T magnet has to be resistive. If it is a DC magnet, the power and the cooling requirements would be extremely high. As a result a continuously cooled repetitive pulsed magnet with a small duty factor (defined as average power/pulse power) would be the economical solution. A 25-30 T, 25 mm bore water cooled repetitive split pulsed magnet with a small duty factor would have a 300~400 kW average power consumption.

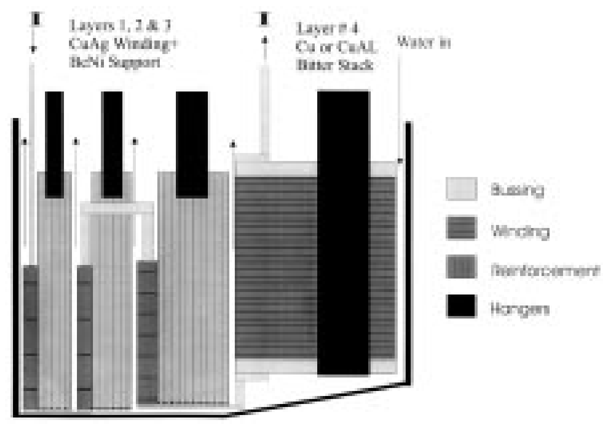

Figure 1. Schematic of the upper right part of a 25-30 T split pulse magnet.

The pulsed neutron source operates at repetition frequencies of 20 Hz as shown in Figure 2. It is desirable to operate the magnet in a synchronized way at the highest repetition rate (20 Hz). To accommodate the magnet cooling requirement, the magnet repetition frequency has to be much lower than the neutron source pulse frequency. We have selected 2 Hz operation frequency to reduce the power requirement by a factor of 10. We have adapted the electrical circuit shown in Figure 3. The operation cycle starts as follows: The capacitor is completely discharged and the charge and voltage changes to opposite polarity in 3 ms. The capacitor charge is reversed during the next 50 ms in the low loss inductor L_1. Then the capacitor voltage is brought back to its original voltage by charging it using the power source in about 300 ms. The capacitor voltage is held a short time before a new cycle starts.

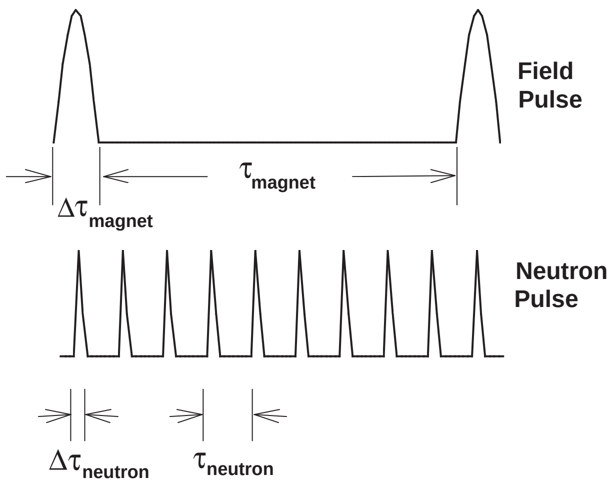

Figure 2. The pulse widths of a spallation neutron source and the pulse magnet $\Delta T_{neutron}$ = 25-100 μs, Δt_{magnet} = 3 μs, $\tau_{neutron}$=50 μs, and τ_{magnet} = 0.5 s.

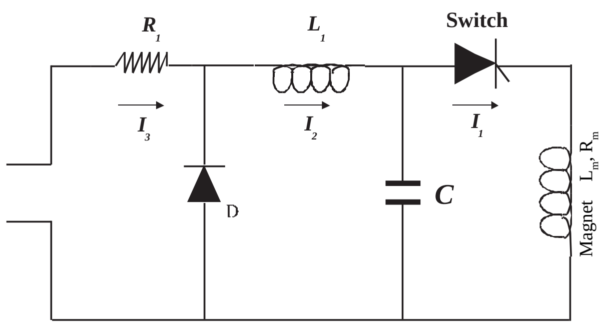

Figure 3. Diagram for the capacitor recharging circuit.

The use of a mechanically de-coupled multi-layer winding reinforced with high modulus structural materials can remove some of the difficulties associated with single stack Bitter coils in generating fields of 25-30 T. The winding has to be made out of a conductor with width smaller than the skin depth to minimize the eddy current loses. The advantages of this concept are: (1) the current carrying region is spread over many layers compared to only one skin depth region in a single layer magnet, thus reducing the power density and temperature rise, and (2) the non-current carrying portion of the disks is replaced by higher modulus material to reduce the stresses in the current carrying region.

Generation of higher fields would require internal reinforcement to limit the stresses below the fatigue limit of known conductors and reinforcement materials. Such a conductor/ internal reinforcement arrangement would increase the stored energy and the ohmic heating power requirement (though the power density is reduced). There is a need to optimize the trade off between the increase in the inductive power due to the introduction of the reinforcements and the decrease in stresses and power density. The success of such system would require a confirmation of the fatigue properties of conductor and reinforcement materials.

A Poly-Layer Reinforcement Scheme for Pulse Magnets

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The inner and outer reinforcement layers of a pulsed magnet, in combination with the high strength conductor, function to contain generated Lorentz forces. Investigations show that considerable stress reduction and a constant von Mises stress distribution in the radial direction within the reinforcement, can be obtained under the condition that the elastic modulus is a function of radius. The technical application of this principle requires that the reinforcement is subdivided into several layers of material each having a different elastic modulus. This poly-layer reinforcement has been studied for isotropic materials including yielding, and orthotropic composites. A significant reduction of the maximum stress at the inner radius may be achieved, with the highest values being obtained for thick cylinders and/or strongly orthotropic materials, such as fiber composites.

At present, there are three principal concepts of pulse magnet design. The conventional one is that of a multi-layer winding reinforced by an outer support shell. A constant current density over the coil volume results with the highest stress at the inner radius. Thus, the maximum field of such a magnet is limited by the strength of the conductor at the inner radius. To reduce the maximum stress, it has been proposed to adjust the current density of each layer to obtain constant stress. This second philosophy has the disadvantage of non-uniform energy dissipation. The third concept combines the advantages of the two previous ones: additional reinforcement is distributed within the body of each layer. Constant current density, i.e. uniform heating and constant stress through the coil can be achieved. Figure 1 shows a comparison of finite element results of von Mises stress for two 10 mm bore, 75 T pulse magnets. The first is a constant current density design magnet with outer reinforcement, and the second utilizes internal and external reinforcement. The results show that the condition of constant von Mises stress can be achieved for the conductor, and that the maximum stress and tangential strain are reduced by approximately half.

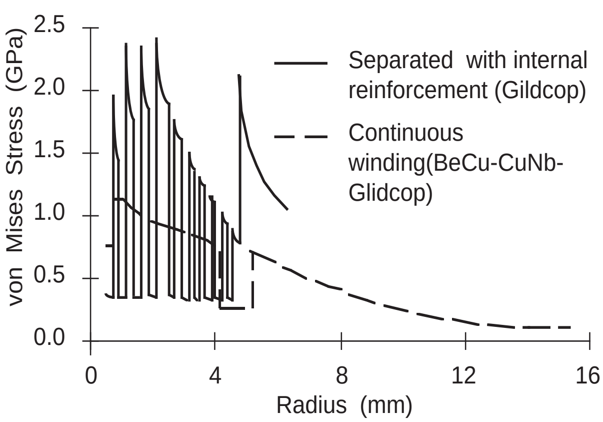

Figure 1. Von Mises stress distribution at the midplane of a 10 mm bore, 75 T pulse magnet.

After having shown that the stress distribution within a magnet can be optimized, we now investigate the question of how to optimize the stress distribution within the reinforcement itself. The idea is to reduce the maximum stress at the inner radius of the reinforcement by

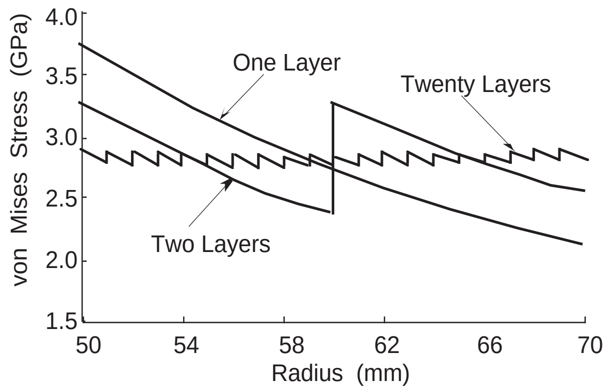

Figure 2. Von Mises stress distribution of an poly-layer isotropic material reinforcement.

subdividing the reinforcement into several layers and optimizing the elastic modulus for each layer. Figure 2 compares the analytical results for the von Mises stress distribution in a one layer, two layer, and twenty layer reinforcement model. The stress is reduced from 3.8 GPa for one layer to 2.9 GPa for twenty layers.

The poly-layer reinforcement method may be utilized to reduce the maximum von Mises stress in the reinforcements. Hence, a higher field may be obtained for the same conductor strength. The success of this method is based upon the availability of materials that have the required elastic modulii.

Conclusions. An analysis for reinforcement with constant von Mises stress in radial direction has been presented for isotropic and orthotropic materials. An ideal radial distribution of the Young’s modulus can be approximated with existing materials. The results show that by utilizing a poly-layer reinforcement with just three materials, a significant stress reduction is achievable. The use of poly-layer reinforcement is pivotal for pulse magnet design where the stress level is high and the available materials capable of being used are limited.

Upgraded User Magnets for the Pulse Facility

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During 1997, two new capacitor powered magnet designs were tested at the Los Alamos Pulse Field Facility that will impact significantly on the resources available to users.

The first of these was a 15 mm bore Al15 Glidcop coil similar in geometry to previous designs but reinforced with a 17 mm A286 steel shell. The magnet was subjected to a total of 19 shots starting from 2000 V and ending at 9950 V. The capacitance of the bank was set to four modules (16.5 mF) throughout the series. The final pulse at 72.75 T can be seen in Figure 1. This compares very favorably with the highest magnetic field ever produced in a capacitor powered magnet of just over 73 T in a bore of ~10 mm. In that instance the coil was destroyed, which was not the case during this test. The time to peak field is almost exactly 6 ms.

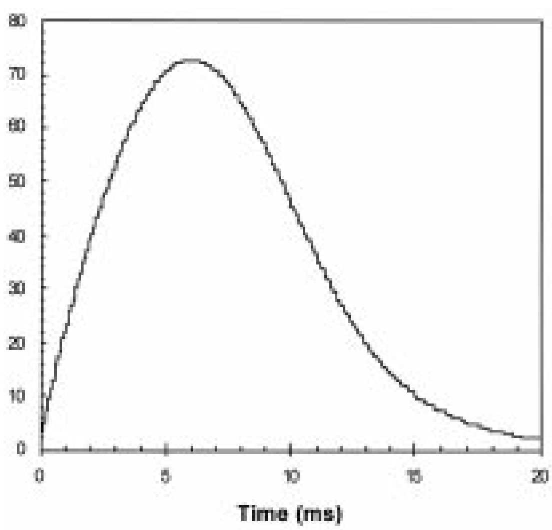

Figure 1. The highest non-destructive magnetic field ever obtained by the NHMFL: 72.75 T in a 15 mm bore, S2 reinforced Glidcop coil with a 17 mm A286 shell.

The cooling time of the magnet is shortened considerably by the use of steel for reinforcing rather than carbon fiber composite. For a 60 T shot, comparing it to the previous standard 12 layer Glidcop, 60 T design the between shot time is reduced from 80 minutes to approximately 40 minutes.

The second coil was designed as a counterpart to the first and as a replacement for the 24 mm, 50 T magnet already in use. This solenoid was manufactured from 3x4mm CuNb reinforced with S2 fiber and externally supported by a 22 mm thick A286 steel shell.

The coil was trained and commissioned with a series of 16 shots. Initially the bank capacitance was set at four modules (16.5 mF) which at 9.95 KV resulted in a field of 59.65 T. The maximum voltage of the bank is 10 KV, thus an extra two modules were added bring the total capacitance to 24.75 mF. An additional five shots were performed, the last at 9.4 KV producing 64.4 T with a rise time of ~7.6 ms. At this point the decision was made to curtail the test because of the significant risk to personnel of a magnet failure while containing almost 1.1 MJ of energy. At no point in the test regime did the magnet give any indications of imminent failure however. Resistance measurements indicate that the coil would be ready for a further shot approximately 45 minutes after the first. This compares with the 60 minutes delay after a standard 50 T shot with the older magnet design.

These coils together will form the new core of capacitor powered magnets for users at the LANL facility. Due to safety considerations, the fields offered will likely be limited to 70 T and 60 T for the 15 mm and 24 mm coils respectively, an increase in 10 T over previous designs. In addition, a considerable increase in the number of shots per day is expected because of the significant decrease in cool down times.

Spectral Element Method for Large-Eddy Simulation of Turbulent Flow in Complex Geometry

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The heat transfer process in high field resistive magnets is being studied through the use of a large-scale flow simulation code developed at the NHMFL. The goal of the project is to better understand and predict the transfer of momentum and heat in rough channels.

The code uses the spectral element method to achieve high spatial accuracy in inhomogeneous directions. The third direction is assumed homogeneous and is developed in Fourier modes. Time integration is performed explicitly on all terms. The fluid (water, in our application) is assumed to be incompressible, although a buoyancy term due to density variations can be modeled via the Boussinesq approximation. The viscosity is allowed to vary in space and time, and is incorporated via a stress tensor.

Incompressibility is enforced by a consistent, elliptic pressure operator. The expansion in Fourier modes in the homogeneous direction reduces the pressure equation to a set of independent Helmholtz operators that are then solved iteratively by a preconditioned conjugate gradient method.

The stress tensor formulation allows for the straightforward implementation of turbulence models for the dissipative effects of unresolved, small-scale motion. The dynamics of large-scale motion in high Reynolds number flows can then be simulated.

The different operators used in the code (e.g. diffusion, convection) have been tested and shown to yield the expected exponential convergence for smooth problems. As a test for the full Navier-Stokes equations, we calculate the flow over a backward-facing step for the case Re=383. The domain decomposition into spectral elements is shown in Figure 1. Steady state isotherms are shown in Figure 2. A plot of the friction coefficient $C_f = 2\tau_w/\rho u^2$ along the bottom wall after the step is given in Figure 3. A negative coefficient corresponds to locally reversed flow. The reattachment length, defined by $C_f = 0$, corresponds well with known experimental and numerical results.

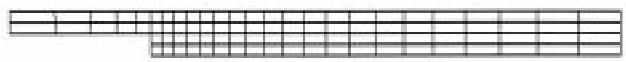

Figure 1. Grid for backstep flow. In each element, the solution is expanded as a tensor product of higher order polynomials (in this case of degree 8).

Figure 2. Isotherms (inlet is set at 10C, walls at 20C). Note the mixing due to reverse flow behind the step, and growth of the thermal boundary layer along the walls.

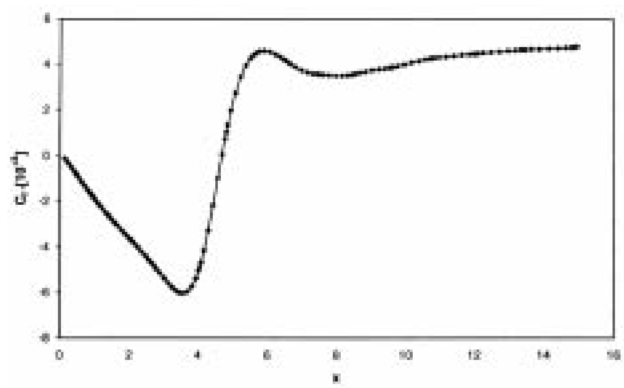

Figure 3. Plot of friction coefficient along bottom wall, for simulation of Re=383 flow.